of corn and soybean rows. Soil Tillage Res. 4:147–154.
Hill, R.L. 1990. Long-term conventional and no-tillage effects on selected soil physical properties. Soil Sci. Soc. Am. J. 54:161–166.
Hill, R.L., and M. Meza-Montalvo. 1990. Long-term wheel traffic effects on soil physical properties under different tillage systems. Soil Sci. Soc. Am. J. 54:865–870.
Maryland Dep. of Agriculture. 1988. Maryland agricultural statistics summary, MDS, Annapolis.
McKeys, E., E. Stemshorn, and R. Bousquet. 1980. Damage to agricultural fields by construction traffic. Trans. ASAE 23(6):1388–1391.
Murphy, J.P., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31–36.
NeSmith, D.S., W.L. Hargrove, D.E. Radcliffe, and E.W. Tollner. 1985. Tillage and residue management for double-cropped soybeans. p. 210. *In* Agronomy Abstracts. ASA, Madison, WI.
Raghaven, G.S.V., E. McKeys, G. Gendron, B. Borglum, and H.H. Le. 1978. Effects of soil compaction on development and yield of corn (maize). Can. J. Plant Sci. 58:435–443.
SAS Institute. 1985. SAS user's guide: Statistics. Version 5. SAS Inst., Cary, NC.
Voorhees, W.B. 1979. Soil tilth deterioration under row cropping in the northern corn belt: Influence of tillage and wheel traffic. J. Soil Water Conserv. 34:184–186.
Voorhees, W.B., J.F. Johnson, G.W. Randall, and W.W. Nelson. 1989. Corn growth and yield as affected by surface and subsoil compaction. Agron. J. 81:294–303.
Voorhees, W.B., W.W. Nelson, and G.W. Randall. 1986. Extent and persistence of subsoil compaction caused by heavy axle loads. Soil Sci. Soc. Am. J. 50:428–433.
Voorhees, W.B., G.C. Senst, and W.W. Nelson. 1978. Compaction and soil structure modification by wheel traffic in the northern Corn Belt. Soil Sci. Soc. Am. J. 42:344–349.
Wilson, H.M., and C.S. Winkelbletch. 1962. A study of soil compaction with wheel equipment. Cornell Univ. Dep. of Agric. Eng.

Border Effects on Yields in a Strip-Intercropped Soybean, Corn, and Wheat Production System

T.K.Iragavarapu* and G.W. Randall

Strip-intercropping of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] normally results in corn producing a negative border effect on soybean production. This study was conducted to determine whether including a small grain strip between corn and soybean strips could reduce the negative border effects of corn and enhance soybean yields. Corn, soybean, and wheat (*Triticum aestivum* L.) were grown as strip intercrops (15-ft wide) in a ridge-till system at two locations in southern Minnesota from 1991 through 1994 and were compared with a two-crop corn-soybean system. Rows were oriented east-west at one location and north-south at the other. Soybean yield in the three-crop system was reduced by 17% for the north row adjacent to corn and 8% for the south row next to wheat compared with nonborder east-west rows. In north-south rows, soybean yields were reduced by 21% in the east row next to corn compared with nonborder rows with no yield reduction in the west row next to wheat. In the two-crop corn-soybean strip system, soybean yields were reduced by 34 and 11% in the south and north border rows, respectively, compared with the nonborder rows in east-west rows. In north-south rows, the outside east row yielded 19% less and the west row yielded 21% less than the nonborder rows. Corn yield of the outside north row next to wheat in east-west rows was 6% greater while the south row next to soybean yielded 18% greater than the nonborder rows. In north-south rows, the east outside row next to wheat yielded 23% greater and the west row next to soybean yielded 27% greater than the nonborder rows. In the two-crop system, yield of the outside corn rows was enhanced similarly compared with the nonborder rows in both row orientations. Wheat yield in the 5-ft section next to soybean was 4% greater than the center 5-ft section and 6% greater than the 5-ft section next to corn in east-west rows and 9 and 17% greater in north-south rows. Results from this 4-yr study indicate that wheat planted between corn and soybean strips improved soybean production over the two-crop system without adversely affecting wheat yields. Corn production was enhanced by 9 to 12% in north-south rows and 2 to 7% in east-west rows in both the two- and three-crop strip systems.

Univ. of Minnesota Southern Exp. Stn., 35838 120th St., Waseca, MN 56093. Minnesota Agric. Exp. Stn. Scientific J. Series Paper no. 21 851. Received 15 May 1995. *Corresponding author (tiragava@smaes.mes.umn.edu).

Published in J. Prod. Agric. 9:101–107.

STRIP INTERCROPPING is a practice in which two or more crops are grown simultaneously in contiguous strips. Alternating narrow strips of tall and short crops has been practiced infrequently for centuries, especially in small, intensive production systems and in developing countries. The goal has been to intercept sunlight more efficiently for maximizing crop production. In the USA, narrow alternate strip cropping systems are becoming more popular, probably because of reduced tillage systems (no tillage and ridge tillage) that easily accommodate management of strips.

In corn-soybean strip intercropping systems, both farmers (Hest, 1984; Holmberg, 1985; Klor, 1986; Reynolds, 1986) and researchers (Pendleton et al., 1963; Crookston and Hill, 1979; West and Griffith, 1992) observed that increased corn yields were offset by decreased soybean yields in the border rows. Radke and Burrows (1970) conducted a study using corn as a temporary windbreak in soybean fields in western Minnesota. They observed that soybean plants adjacent to corn windbreaks were not as productive as the rest of the windbreak-sheltered soybean due to shading and root competition from corn. Lesser soybean yields have been attributed to competition between corn and soybean for water, light, and nutrients due to the similarities in growth habits of the crops (Crookston and Hill, 1979).

A new approach to strip cropping, practiced by some farmers in the upper Midwest (Cramer, 1991; Mangold, 1992; Tonneson and Houtsma, 1991; Walter, 1991), introduces a

small grain crop (either oats [*Avena sativa* L.] or wheat) into the traditional two-crop system. Including a small grain strip between corn and soybean strips should reduce negative border effects on adjacent soybean rows without sacrificing wheat yields. Wheat, a cool season crop, is less affected by shading because it matures before shading by the corn becomes excessive. When a small grain was planted between corn and soybean strips, researchers in Iowa (Ghaffarzadeh et al., 1994) observed that in north-south rows, the soybean row adjacent to the small grain strip yielded 16% less than the row next to corn in a dry year while the soybean row next to small grain yielded 49% greater than the row adjacent to corn in a wet year. No differences were found between the two border rows in either a wet or dry year at the east-west row location. Also, in a dry year, corn yield was 50% less in north-south rows and 12% less in east-west rows in the row adjacent to the small grain strip compared with the row next to soybean. The researchers observed, however, that the small grain was consistently unaffected by either the corn or soybean border crops. On the other hand, studies conducted in Canada (Fortin et al., 1994) reported that in north-south rows, soybean yields in the row adjacent to small grain were 18% and 25% greater in a dry and wet year, respectively, than the row next to corn. In a dry year, however, corn yield was 26% less in the row adjacent to small grain than in the row next to soybean.

From these two studies it is clear that small grain competes with corn for moisture in dry years. The effect of the small grain strip on soybean production is not clear in these three-crop strip rotations, however. The objectives of this study were to: (i) determine the border effects of wheat introduced between corn and soybean strips on grain yield of soybean and corn and on corn grain moisture at harvest, and (ii) compare grain yield of soybean and corn in the three-crop system to that in the two-crop corn-soybean system.

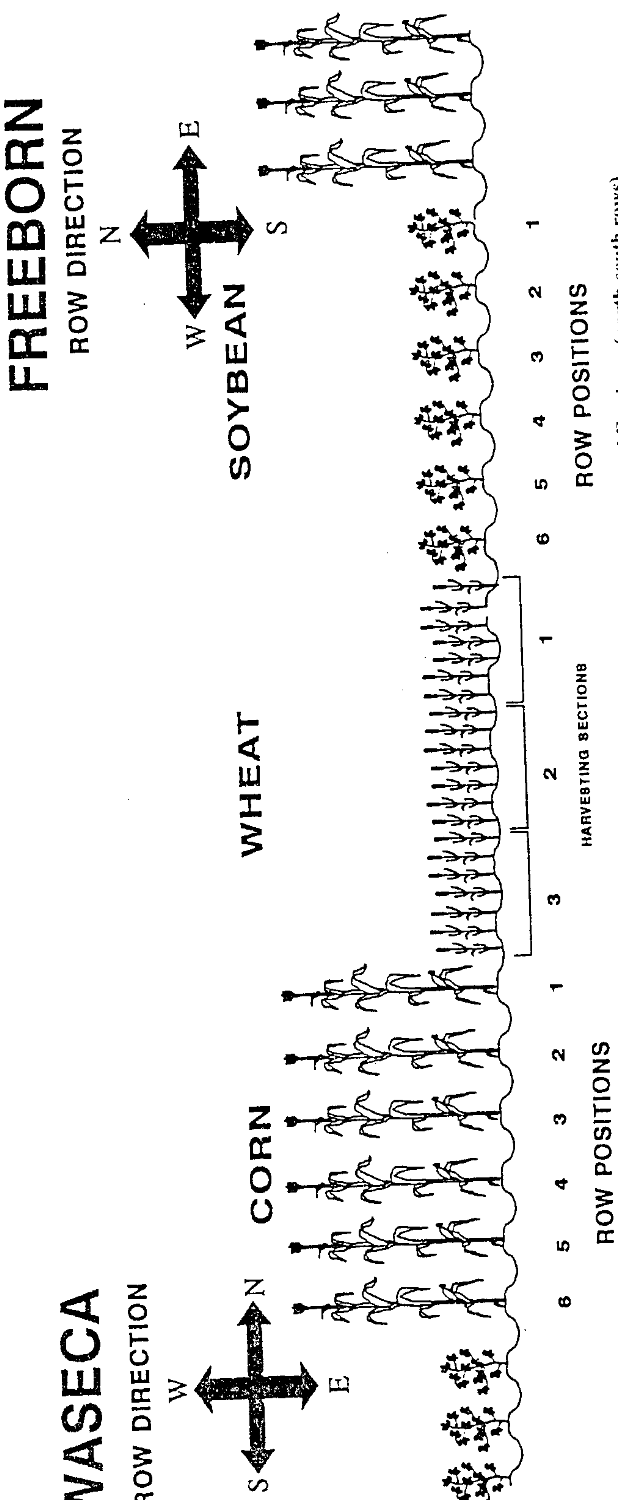

Fig. 1. Schematic diagram of corn, soybean, and wheat strip-intercropping at Waseca (east-west rows) and Freeborn (north-south rows).

MATERIALS AND METHODS

Field experiments were conducted from 1991 through 1994 at two sites located 30 miles apart in southern Minnesota. Rows were oriented east-west at Waseca and north-south at Freeborn. At both locations, the soil type is a poorly drained Webster clay loam (fine-loamy, mixed, mesic Typic Haplaquoll). Soybean was grown on ridges in all strips at both sites in 1990.

Beginning in 1991, wheat, corn, and soybean were planted as strip-intercrops on ridges. Each crop was planted in a 15-ft wide by 120-ft long strip allowing for six rows each of corn and soybean and 21 rows of wheat per strip. Soybean strips were located on the south side and wheat strips on the north side of corn at Waseca (Fig. 1). This arrangement minimized shading at the strip borders because the wheat on the north side of the corn was almost mature by the time of shading by the corn. In the north-south rows at Freeborn, wheat was located on the east side and soybean on the west side of the corn strips. Corn and soybean rows were numbered 1 through 6, starting from the north at Waseca and east at Freeborn. Crops were rotated each year so that corn followed wheat, soybean followed corn, and wheat followed soybean. Corn and soybean were also planted and rotated in a two-crop alternate strip system within each replication at both locations. Insufficient space within each replication did not allow

room for a border strip between the two- and three-crop systems.

Corn 'Pioneer hybrid 3751' and soybean 'Sturdy' were planted on the same day in 30 in. rows with a six-row planter on ridges that were scalped to remove 1 to 2 in. of soil and the previous crop residue. Planting rate of the corn border rows (1 and 6) was increased by 20% above the nonborder rows (30 200 plants/acre) in an effort to maximize corn production within both the two- and three-crop systems. Soybean was planted at 9 to 10 seeds/ft of row. Spring wheat 'Grandin' was planted at 94 lb/acre directly into the soybean stubble without secondary tillage using a no-till drill following an application of 50 lb N/acre as ammonium nitrate. Each corn strip was subdivided into four 30-ft long plots and ammonium nitrate, was broadcast at rates of 0, 40, 80, and 120-lb N/acre. Starter fertilizer was not applied. Corn yields from only the 120-lb N/acre rate, which is close to the optimum N rate for corn after wheat and soybean, are presented and discussed in this paper. Phosphorus and K fertilizer were not applied due to high soil test levels of these nutrients. Corn and soybean strips were cultivated twice; with the second cultivation serving to build the ridges for the following year. Ridges were built when the corn and soybean reached about 20-in. height. Alachlor (3.0 lb ai/acre) and cyanazine (2.5 lb ai/acre) were tank-mixed and applied as preemergence herbicides for corn. For soybean, alachlor (3.0 lb ai/acre) was applied as pre-emergence and imazethapyr (0.06 lb ai/acre) was applied at the first trifoliate stage. All herbicides were applied in a 15-in. band. Bromoxynil (0.25 lb ai/acre) was broadcast to wheat before flagleaf stage to control broadleaf weeds.

Corn yield was determined by hand-harvesting 25-ft of each row. Soybean was harvested with a plot combine. Wheat yields were determined from each row by hand-harvesting a 15-ft long section. For the purpose of this paper, wheat grain yields were expressed for center and outside one-third sections, each 5-ft wide, by averaging yields from all seven rows for each section. Grain moisture at harvest was recorded for all three crops.

Relative grain yields for all corn and soybean rows, as well as the whole strip, were calculated by comparing the yields of each row to the center two rows within each six-row strip system. The experimental design was a randomized, complete block design with four replications. The effects of row position on grain yield and grain moisture were tested by analysis of variance with row positions and blocks as sources of variation for each year and location separately. In a combined analyses across the 4 yr, years and year × row position were also included as sources of variation within each location. The statistical analyses were performed using the general linear model procedure of SAS (SAS Inst, 1988). Row means were compared with single degree of freedom contrasts and Fisher's protected LSD at 5% level.

RESULTS AND DISCUSSION

Weather Conditions

Weather conditions during the growing season varied considerably among years but were similar at both locations (Table 1). Growing season was ideal in 1991, with abundant rainfall and warmer-than-normal temperatures. Rainfall was slightly below normal early in the growing season in 1992 and temperatures were colder than normal throughout the season. Conditions for plant growth were far from ideal in 1993, with excessive rainfall between May and August and cooler-than-normal air temperatures. Air temperatures in 1994 were above normal early in the growing season and again in September with cooler-than-normal July and August. Rainfall in 1994 was close to normal during the growing season, but below normal in May.

Soybean Yield

At the Waseca site with east-west rows, the north outside row next to corn yielded 17% less ($P \leq 0.01$) while the south outside row next to wheat yielded 8% less ($P \leq 0.01$) than the nonborder rows (Table 2). A combined analysis showed a significant ($P \leq 0.05$) effect of both years and year × row position interaction on soybean seed yield at Waseca. At the Freeborn site with north-south rows, the east outside row next to corn yielded 21% less ($P \leq 0.01$) than the nonborder rows, while the west outside row next to wheat yielded similar to the nonborder rows when averaged across years. Years had a significant effect ($P \leq 0.05$), while the year × row position interaction was nonsignificant in a combined analyses at Freeborn. Soybean yield in the row adjacent to corn was reduced on average by 10% ($P \leq 0.05$) at Waseca (east-west rows) and 18% ($P \leq 0.01$) at Freeborn (north-south rows) compared with the row next to wheat during the 4 yr. Fortin et al. (1994) also reported about 18% yield loss for the row next to corn compared with the row next to small grain in north-south rows. Seed size among the rows was very inconsistent with small seeds occurring in 2 of 6 site-yr in the row next to corn and larger seeds occurring in the row next to wheat in only 1 of 6 site-yr (data not shown). Other possible reasons for lesser yield of the outside soybean row are fewer pods and seeds per pod than in the nonborder rows.

In the two-crop system when both outside soybean rows were bordered by corn, row position influenced seed yield ($P \leq 0.05$) in all 7 site-yr (Table 3). The south outside row at Waseca yielded 34% less than the interior rows while the north row yielded 11% less during the 4 yr. Moreover, the outside south row yielded 25% less ($P \leq 0.01$) than the north row. The reason for the south row suffering more yield loss than the north row at Waseca is assumed to be due mainly to shading by the corn. At Freeborn, the east outside row yielded 19% less than the nonborder rows during the 3 yr, while the west outside row yielded 21% less in 2 yr. Yield differences were not significant between the two outside rows in the north-south rows.

Soybean yield in row 6 (adjacent to wheat) in the three-crop system (Table 2) was 8% less than the nonborder rows across years at Waseca and only 3% less at Freeborn. On the other hand, row 6 adjacent to corn in the two-crop system (Table 3) yielded 34% less across years at Waseca and 21% less at Freeborn. Thus, small grain resulted in less competition with the neighboring soybean row than corn, and soybean yields were greatly improved for the three-crop system. Root studies conducted in western Minnesota (Nelson and Allmaras, 1969; Radke and Burrows, 1970) showed corn roots proliferating into the adjacent soybean row and competing with soybean for moisture and nutrients. These researchers also observed very little intermingling of the roots from two adjacent soybean rows or two adjacent corn rows. This competition between adjacent corn and soybean roots may

Table 1. Growing season (Apr-Sept) and mean monthly air temperature and rainfall compared with the long-term normals at Waseca and Freeborn.

Location	Month	Air temperature, °F: 30-yr normal†	1991	1992	1993	1994	Rainfall, in.: 30-yr normal†	1991	1992	1993	1994
			Deviation from normal					Deviation from normal			
Waseca	April	44.6	4.0	−2.8	−2.0	0.4	3.0	1.3	0.2	2.1	2.6
	May	57.6	3.4	2.6	−1.0	2.8	3.6	4.1	−0.7	2.5	−2.0
	June	67.1	6.3	−0.9	−2.0	3.1	4.1	−0.4	−0.2	2.7	−0.8
	July	71.2	0.7	−6.4	−1.1	−3.0	4.2	4.5	0.1	2.9	0.7
	August	68.3	2.2	−3.0	1.8	−1.7	4.2	2.1	1.8	4.1	0.8
	Sept.	59.5	−0.3	−0.9	−4.3	4.6	3.6	1.0	−0.3	−0.3	0.8
	Apr–Sept.	61.4	2.7	−1.9	−1.4	1.0	22.7	12.6	0.9	14.0	2.1
Freeborn	April	44.8	3.5	−3.3	−2.7	0.6	2.9	2.4	−0.2	2.2	0.8
	May	57.9	2.9	1.6	−1.3	2.1	3.5	3.4	−1.3	2.6	−1.4
	June	67.6	5.4	−1.6	−2.7	2.6	4.3	0.1	−1.5	3.7	0.2
	July	71.9	0.0	−7.0	−1.9	−3.6	4.3	1.7	0.9	2.8	1.1
	August	69.0	1.2	−4.1	0.9	−2.3	4.0	1.1	0.9	5.0	0.5
	Sept.	59.9	−0.7	−1.6	−4.9	4.2	3.4	−0.1	−0.6	0.1	1.5
	Apr–Sept.	61.8	2.0	−2.7	−2.1	0.6	22.4	8.6	−1.8	16.4	2.7

† 1961–1990 normals.

Table 2. Soybean yield in a corn-soybean-wheat strip-intercropping system at Waseca (east-west rows) and Freeborn (north-south rows).

Row	East-west rows: 1991	1992	1993	1994	Average	North-south rows: 1991	1992	1993	1994	Average
	bu/acre									
1 (next to corn)	31.8	31.4	30.5	34.6	32.1	27.4	29.0	20.9	33.4	27.7
2	33.3	37.1	30.6	44.8	36.4	34.3	32.8	25.7	45.3	34.5
3&4	39.9	41.0	31.0	44.5	39.1	35.4	36.9	23.2	46.2	35.4
5	39.8	41.1	31.9	47.2	40.0	39.5	38.2	21.4	43.1	35.5
6 (next to wheat)	40.9	35.0	29.7	37.2	35.7	40.1	34.5	20.6	40.7	34.0
CV, %	10.2	7.6	10.9	8.3	9.2	10.4	18.4	13.1	8.8	13.0
LSD (0.05)	5.8	4.4	NS	5.2	2.4	5.6	NS	NS	5.7	3.1
Row contrasts:										
1 vs. 2-5	*	**	NS	**	**	**	†	NS	**	**
6 vs. 2-5	NS	*	NS	**	**	NS	NS	NS	†	NS
1 vs. 6	**	†	NS	NS	*	**	NS	NS	*	**
2&5 vs. 3&4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, †, and NS = significant at 0.05, 0.01, and 0.10 probability levels and not significant at 0.10 probability level, respectively.

Table 3. Soybean yield in a corn-soybean strip-intercropping system at Waseca (east-west rows) and Freeborn (north-south rows).

Row	East-west rows: 1991	1992	1993	1994	Average	North-south rows: 1992	1993‡	1994	Average
	bu/acre								
1 (next to corn)	26.7	36.3	32.4	45.7	35.3	27.0	15.8	39.6	27.5
2	31.4	39.6	34.5	48.7	38.5	31.9	22.3	42.3	32.2
3&4	38.2	42.0	34.3	49.9	41.1	38.2	22.1	46.3	35.5
5	39.5	34.3	33.4	45.0	38.0	35.3	21.6	41.1	32.7
6 (next to corn)	25.9	23.5	23.8	32.0	26.3	27.5	--	35.6	--
CV, %	9.9	6.2	6.8	5.6	6.7	11.2	6.1	10.0	8.1
LSD (0.05)	8.9	6.0	6.0	3.8	2.3	6.7	2.5	6.3	2.5
Row contrasts:									
1 vs. 2-5	*	NS	NS	NS	**	**	**	NS	**
6 vs. 2-5	*	**	**	**	**	*	--	**	--
1 vs. 6	NS	**	*	**	**	NS	--	NS	--
2&5 vs. 3&4	NS	†	NS	†	*	NS	NS	†	**

*, **, †, and NS = significant at 0.05, 0.01, and 0.10 probability levels and not significant at 0.10 probability level, respectively.
‡ Row 6 borders corn in two replications and wheat in another two replications and was not considered in analysis.

largely explain the soybean yield loss in the row adjacent to corn at Freeborn in north-south rows and in the soybean row south of corn at Waseca where shading never occurred. Averaged across years, soybean seed moisture was not influenced over 0.3 percentage points by row position at either the Waseca or Freeborn sites (data not shown).

Corn Grain Yield and Moisture

A combined analysis of variance showed a significant effect ($P \leq 0.05$) of both years and year × row position interaction on corn grain yield at both locations. Corn grain yields were highest in 1991 due to abundant moisture and warm temperatures while lowest grain yields were recorded in 1993 due to the unusually cool and wet conditions. In the three-crop strip system, corn yields of the individual rows were affected by row position ($P \leq 0.05$) from 1991 to 1993 at both locations (Table 4). Weeds, especially dandelions (*Taraxacum officinale* Weber), were a problem in 1994 at both locations, especially in the strips where wheat was grown in 1993. Weed pressure coupled with high levels of wheat residue posed problems in establishing a uniformly emerging stand leading to nonsignificant yield differences among the rows. Averaged across the 4 yr, the north outside

Table 4. Corn yield in a corn-soybean-wheat strip-intercropping system at Waseca (east-west rows) and Freeborn (north-south rows).

Row	East-west rows 1991	1992	1993	1994	Average	North-south rows 1991	1992	1993	1994	Average
	bu/acre									
1 (next to wheat)	169.3	181.2	125.8	140.8	154.3	217.9	195.2	123.6	138.6	168.8
2	161.0	159.1	105.5	134.1	139.9	173.4	159.3	97.9	129.6	140.0
3	176.0	155.9	107.1	147.1	146.5	161.6	155.2	91.4	145.4	138.4
4	171.2	170.2	113.9	149.0	151.1	154.4	155.7	95.4	131.8	134.3
5	176.4	163.0	99.0	129.7	142.0	173.6	157.5	87.4	123.1	135.4
6 (next to soybean)	216.3	187.1	128.8	150.9	170.8	251.3	187.2	119.7	149.3	176.9
CV, %	5.3	7.0	8.5	10.6	7.8	10.8	8.4	9.0	12.8	10.6
LSD (0.05)	14.3	17.8	14.5	NS	8.3	30.8	21.4	14.0	NS	11.2
Row contrasts:										
1 vs. 2-5	NS	*	**	NS	**	**	**	**	NS	**
6 vs. 2-5	**	**	**	NS	**	**	**	**	NS	**
1 vs. 6	**	NS	NS	NS	**	*	NS	NS	NS	NS
2&5 vs. 3&4	NS	NS	NS	†	**	NS	NS	NS	NS	NS

*, **, †, NS = significant at 0.05, 0.01, and 0.10 probability levels and not significant at 0.10 probability level, respectively.

Table 5. Corn yield in a corn-soybean strip-intercropping system at Waseca (east-west rows) and Freeborn (north-south rows).

Row	East-west rows 1991†	1992‡	1993†	1994‡	North-south rows 1991†	1992‡	1993†	1994‡
	bu/acre							
1	--	197.5	--	207.4	--	208.2	--	179.2
2	189.9	167.8	121.1	175.9	165.4	154.5	85.1	143.1
3	183.4	162.9	128.2	169.0	157.8	158.4	94.7	146.0
4	187.0	163.1	124.9	183.1	139.9	154.0	95.4	136.8
5	193.2	155.7	125.3	163.5	151.9	147.8	102.0	123.5
6	235.8	--	151.3	--	243.6	--	114.9	--
CV, %	6.3	8.6	6.5	6.2	5.7	6.6	11.3	8.0
LSD (0.05)	19.1	22.5	13.0	17.2	18.0	16.8	NS	21.9
Row contrasts:								
1 vs. 2-5	--	**	--	**	--	**	--	**
6 vs. 2-5	**	--	**	--	**	--	*	--
2&5 vs. 3&4	NS	NS	NS	NS	NS	NS	NS	NS

*, **, NS = significant at 0.05, and 0.01 probability levels, and not significant at 0.10 probability level, respectively.
† Row 1 bordered corn and was not considered in the analysis.
‡ Row 6 bordered corn and was not considered in the analysis.

row at Waseca yielded 6% more while the south row yielded 18% more than the nonborder rows. This advantage for the outside corn rows could be due to a combination of better light interception and increased population in these rows. Greater yield advantage for the south outside row is thought to be due mainly to more direct sunlight reaching this row than the north row. This indicates that the yield advantage for strip intercropping is due mainly to the south row when in an east-west row orientation. On the other hand, at Freeborn with north-south rows, both the east and west outside rows benefitted by strip cropping. Averaged across years, yields of the east and west outside rows were 23 and 27% greater, respectively, than the nonborder rows. Unlike Waseca, yield differences were not significant between the outside east and west rows at Freeborn, probably because of similar amounts of sunlight reaching both outside rows.

Corn yields in the two-crop system were also influenced by row position in 7 of 8 site-yr (Table 5). At Waseca, the outside north row yielded 21% more than the nonborder rows, while the yield advantage for the outside south row averaged 23% above the nonborder rows. At Freeborn, the east outside row yielded 30 to 35% greater than the nonborder rows while the west outside row had a yield advantage of 58% in 1991 but only 22% in 1993 when yields were low and variable. When comparing the two- and three-crop systems in the same years (1991 and 1993), the corn row adjacent to soybean yielded 23% greater at Waseca and 40% greater at Freeborn than the nonborder rows in both cropping systems. This indicates that the outside corn row adjacent to soybean markedly and equally benefits both the two- and three-crop strip systems, especially when planted in a north-south row orientation.

Grain moisture at harvest of the outside north row next to wheat was significantly greater than the nonborder rows when averaged across years at Waseca (Table 6). On the other hand, the corn row next to soybean had significantly less grain moisture than the nonborder rows. Averaged across years, grain moisture in the south row was 4.2 percentage points

Table 6. Corn grain moisture at harvest in a corn-soybean-wheat strip-intercropping system at Waseca (east-west rows) and Freeborn (north-south rows).

Row	East-west rows 1991	1992	1993	1994	Average	North-south rows 1991	1992	1993	1994	Average
	%									
1 (next to wheat)	37.5	31.0	36.4	30.1	33.7	21.3	22.9	23.4	26.2	23.4
2	36.6	29.5	33.2	30.8	32.5	22.1	21.8	24.2	25.8	23.5
3	36.2	28.5	33.8	28.7	31.8	21.6	25.1	24.1	27.3	24.5
4	36.2	27.4	33.2	28.4	31.3	21.8	23.4	24.5	26.4	24.0
5	35.2	25.6	34.8	30.4	31.5	21.8	21.5	24.7	26.1	23.5
6 (next to soybean)	35.5	23.9	32.3	26.3	29.5	20.3	21.3	23.1	26.2	22.7
CV, %	1.6	5.2	6.2	4.7	4.6	3.4	4.4	4.8	6.3	5.0
LSD (0.05)	0.9	2.1	NS	2.1	1.0	1.1	1.5	NS	NS	0.8
Row contrasts:										
1 vs. 2-5	**	**	*	NS	**	NS	NS	NS	NS	NS
6 vs. 2-5	NS	**	NS	**	**	**	*	†	NS	**
1 vs. 6	**	**	*	**	**	†	*	NS	NS	†
2&5 vs. 3&4	NS	NS	NS	**	NS	NS	**	NS	NS	**

*, **, †, NS = significant at 0.05, 0.01, and 0.10 probability levels and not significant at 0.10 probability level, respectively.

Table 7. Wheat grain yields in a corn-soybean-wheat strip-intercropping system at Waseca and Freeborn.

Year	Position in the strip			CV	LSD (0.05)
	bu/acre			%	bu/acre
East-west rows	North 1/3	Center 1/3	South 1/3		
1991	33.5	33.0	31.9	4.8	NS
1992	67.6	65.5	65.8	2.1	NS
1993	31.2	29.9	27.9	9.5	NS
1994	42.2	39.6	39.1	4.7	NS
Average	43.6	42.0	41.2	4.7	1.5
North-south rows	East 1/3	Center 1/3	West 1/3		
1991	42.6	38.2	32.2	11.1	7.3
1992	59.2	55.4	52.1	8.2	NS
1993	30.5	31.4	31.0	7.7	NS
1994	36.2	29.6	28.5	15.7	NS
Average	42.1	38.6	35.9	10.6	3.0

NS = not significant at 0.10 probability level.

drier ($P \leq 0.01$) than the north row. This probably is due to the south row receiving more direct sunlight than the north outside row. At Freeborn, averaged across years, grain moisture of the east outside corn row next to wheat was not drier, while the west outside row was 1.2 percentage points drier ($P \leq 0.01$) than the nonborder rows. This is probably because the west outside corn row receives the sun late in the afternoon when temperatures are generally higher and humidities lower resulting in faster drydown in this row. Similar results were found with the two-crop system at both locations (data not shown). These results suggest that energy costs for artificial drying could be reduced when intercrop strips are planted in a north-south row orientation. But when planted in an east-west direction, the higher moisture content in the north row offsets the lower grain moisture in the south row and energy savings would not be realized.

Wheat Grain Yield

In a combined analyses across the 4 yr, years were significantly different ($P \leq 0.05$) while the year × position interaction was not for wheat grain yield at both locations. Although not statistically significant within years, wheat grain yields in the 5-ft section next to soybean were greater than either the 5-ft section in the center or next to corn in 7 of 8 site-yr (Table 7). When analyzed across years, the higher degrees of freedom for error term in a combined analysis gave more power in detecting a significant ($P \leq 0.05$) difference among these strip positions. At Waseca, the north 5-ft section next to soybean yielded 4 and 6% more than the center and south (next to corn) 5-ft sections, respectively. The 4-yr average yield in the east 5-ft section adjacent to soybean was 9 and 17% greater than the center section and the west 5-ft section next to corn at Freeborn. This could be due to enhanced wheat yields in the rows next to soybean or reduced wheat yields in the border rows next to corn due to some competition for light, moisture, and nutrients between the small grain and the corn. Averaged across years, wheat grain moisture was similar among the strip positions at Waseca while the center 5-ft portion of the strip at Freeborn had 0.7 and 0.9 points less ($P \leq 0.05$) grain moisture than the west and east 5-ft sections, respectively (data not shown).

Strip vs. Whole Field Comparisons

Results from this 4-yr study show that the border effects on grain yields of corn and soybean are quite evident in this

Table 8. Relative grain yield of corn, soybean, and wheat strips averaged across years compared with a whole field at Waseca (east-west rows) and Freeborn (north-south rows)†.

Row	East-west rows			North-south rows		
	Corn	Soybean	Wheat	Corn	Soybean	Wheat
	Relative grain yield, %					
1	104	82	104	124	78	109
2	94	93		103	98	
3	100	100	100	100	100	100
4	100	100		100	100	
5	96	102	98	99	100	93
6	115	91		130	96	
Whole strip	102	95	101	109	95	101

† Assuming that the center 5 ft of each strip represents a whole field.

Table 9. Relative grain yield of corn and soybean strips averaged across years compared with a whole field at Waseca (east-west rows) and Freeborn (north-south rows)†.

Row	East-west rows		North-south rows	
	Corn	Soybean	Corn	Soybean
	Relative grain yield, %			
1	120‡	86	130‡	78
2	100	93	100	91
3	100	100	100	100
4	100	100	100	100
5	98	92	98	92
6	123‡	64	142‡	74‡
Whole strip	107	89	112	89

† Assuming that the center 5 ft of each strip represents a whole field.
‡ Two-year averages for these rows.

six-row strip-intercropping study. However, a farmer's decision regarding adopting strip-intercropping would be based on relative yield advantage calculation of corn and soybean grown in strips vs. whole fields. The statistical analyses in tables 2 and 4 indicate that grain/seed yields in the second row from outside (rows 2 and 5) are similar to the center two rows (rows 3 and 4) in 15 of 16 site-yr. This suggests that measurable border effects in these six-row strips are confined only to the two outside rows. Similar results were shown by West and Griffith (1992) in eight-row strips. Even though we did not have whole blocks of corn and soybean to make strip vs. whole field comparisons, we contend that the yield of the center two rows of this six-row strip system represent (within plus or minus 0 to 5%) the whole-field yields. Therefore, we assumed that the center two rows (5 ft) of the 15-ft strip represent a whole-field yield, and we calculated relative grain yield for each individual row compared with a whole-field yield based on 4-yr averages. As indicated by the relative grain yield, soybean yields were improved by 9% in the row next to wheat (row 6) in east-west rows and 18% in north-south rows compared with the row next to corn (row 1) (Table 8). Overall soybean strip yields were 5% lower in both row orientations than in a whole-field. Strip intercropping benefitted corn yields, especially in north-south rows. Corn yields in the strips were improved mainly due to the south row in east-west rows (2% overall) and both the east and west outside rows in north-south planted fields (9% overall) (Table 8). Reduced wheat yields in the 5-ft section next to corn compared with the center 5-ft section was offset by increased yields in the 5-ft section next to soybean resulting in overall strip yields similar to the whole-field averages at both locations. In the two-crop system (Table 9), soybean yield loss in the strips was greater due to both outside rows yielding less than the center two rows, resulting

in an 11% yield loss at both locations. Whole strip corn yields were enhanced by 7 to 12% due to greater positive effects in the border rows in both row orientations in the two-crop system (Table 9).

CONCLUSIONS

Results from this 4-yr study indicate that under southern Minnesota conditions, wheat planted on the north side of corn in east-west rows and east of corn in north-south rows reduces negative border effects on soybean and improves the overall strip yields compared with a two-crop corn-soybean system. The soybean border row next to wheat benefitted more when planted in north-south rows than in east-west rows. Corn yields of the strips were considerably greater than whole-field yields due to positive border effects on outside rows, especially when planted in north-south rows. Energy costs for artificial drying could be reduced somewhat due to drier corn grain in both outside rows when intercrop strips are planted in a north-south row orientation. Although wheat yields were reduced slightly in the 5-ft section next to corn, the overall strip yields were unaffected due to strip cropping. These results suggest that alternate three-crop strips should be planted in a north-south row orientation rather than east-west to optimize production. However, economic conditions will determine the net benefit of farmers adopting this three-crop strip system rather than the two-crop system or the normal whole-field planting.

ACKNOWLEDGEMENT

The authors gratefully extend their appreciation to assistant scientists Brian Anderson and Jeffrey Vetsch for their role in the collection of data by the field technicians. We are also grateful to Lynn Sorenson, farmer-cooperator in Freeborn County, for his continued assistance throughout this study. We thank Drs. Steve Simmons and Michael Schmitt for their helpful comments and suggestions in the internal review of this manuscript. This project was supported in part by grants from the Minnesota Department of Agriculture Sustainable Agriculture Program (contract no. 04651-21330) and from the Sustainable Agriculture Research and Education program through the USDA Cooperative State Research, Education, and Economic Service under cooperative agreement no. 88-COOP-1-3523. Any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the USDA.

REFERENCES

Cramer, C. 1991. Strips boost yields, save soil. New Farm. February, p. 14–18.

Crookston, R.K., and D.S. Hill. 1979. Grain yields and land equivalent ratios from intercropping corn and soybean in Minnesota. Agron. J. 71:41–44.

Fortin, M.C., J. Culley, and M. Edwards. 1994. Soil water, plant growth, and yield of strip-intercropped corn. J. Prod. Agric. 7:63–69.

Ghaffarzadeh, M., F.G. Prechac, and R.M. Cruse. 1994. Grain yield response of corn, soybean, and oat grown in a strip intercropping system. Am. J. Altern. Agric. 9: 171–177.

Hest, D. 1984. Corn-bean strips enrich return prospects. The Farmer. March, p. 56–57.

Holmberg, M. 1985. Strip cropping: More corn, less beans, more profit. Successful Farming. March, p. 18–19.

Klor, D. 1986. Strips boost yields, profits. New Farm. February, p. 15–17.

Mangold, G. 1992. Farmers test stripcrops. Soybean Digest. March, p. 28–32.

Nelson, W.W., and R.R. Allmaras. 1969. An improved monolith method for excavating and describing roots. Agron. J. 61:751–754.

Pendleton, J.W., C.D. Bolen, and R.D. Seif. 1963. Alternating strips of corn and soybeans vs. solid plantings. Agron. J. 55:293–295.

Radke, J.K., and W.C Burrows. 1970. Soybean plant response to temporary field windbreaks. Agron. J. 62:424–429.

Reynolds, R. 1986. 6 x 6 = $18/A more. New Farm. February, p. 12–14.

SAS Institute. 1988. SAS user's guide. Statistics. 6 ed. SAS Inst., Cary, NC.

Tonneson, J., and J. Houtsma. 1991. Adding new wrinkles to alternate strips. The Farmer. September, p. 8–9.

Walter, J. 1991. Strips with kick. Successful Farming. January, p. 26–27.

West, T.D., and D.R. Griffith. 1992. Effect of strip-intercropping corn and soybean on yield and profit. J. Prod. Agric. 5:107–110.